Theoretical Experimental and Studies on the Influence of the Mast Mounted Sight (MMS) on the Dynamic Behavior of the Focal Isolation System (FIS) of Helicopter

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Abstract: This paper presents a theoretical-cum-experimental study on the dynamic behavior of Focal Isolation System of helicopter equipped with Mast Mounted Sight. A new simplified model of FIS/MMS/Fuselage with 5-Degree of Freedom (DOF) is proposed, where elasticity of the rotor shaft and the support structure of MMS are taken into account. In order to validate this model and make further investigation on MMS, a dummy MMS and its support are fabricated. Frequency and transfer function experiments are carried out on Z-× helicopter. Good correlation between theoretical and experimental results is achieved. A 39% decrease in 1st longitudinal frequency is noticed for FIS when the mass of MMS is 80kg, which is only 12% of the mass to be isolated. The elasticity of rotor shaft has great influence (403%) on the isolation efficiency of fuselage for prototype.

Key words: frequency; MMS; focal isolation system; helicopter

桅杆式瞄准具对直升机聚焦式隔振系统动态特性的影响研究. 王荇卫, 程 伟, 诸德超, 黄斌根, 凌爱民. 中国航空学报(英文版), 2003, 16(4): 217-222.

摘 要: 对直升机加装桅杆式瞄准具后, 聚焦式隔振系统的特性进行了分析与试验研究。考虑旋转翼轴、桅杆支撑结构的弹性影响, 提出了一个新的5个自由度的桅杆/隔振系统/机身耦合模型。为了验证该模型并有利于桅杆式瞄准技术的进一步研究, 加工了一套瞄准具假件及其支撑结构, 并在直-×型机上进行了频率和传递函数测试, 计算结果与试验结果吻合。研究表明, 加装80kg 的瞄准具(被隔振重量的12%), 聚焦式隔振系统的一阶频率下降了39%; 结构弹性对隔振系统隔振效率有很大影响, 即使是原型机也达到了403%。

关键词: 频率; 桅杆式瞄准具; 聚焦式隔振系统; 直升机

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1 Introduction

In order to improve the survivability of attack helicopter or scout helicopter, MMS has been used. OH-58D scout helicopter is the first one equipped with MMS[1], and has shown great advantages of MMS during the war. This is the main reason why so many kinds of attack helicopter have chosen mast mounted configuration, such as AH-64D, Tiger and Mi-28N [2].

One of the critical problems, which have to be solved before the sight mounted to the head of rotor, is the dynamical one which is very important to both helicopter and MMS itself [3, 4]. It is well known that the rotor system is the main vibration resource of helicopter. Usually, there is a vibration isolator between main gearbox and airframe to decrease the dynamical load transfered from the rotor to the airframe, and the frequency of the isolation system is usually set to 1/3 to 1/2 of the forcing frequency of rotor. With sight mounted, the fre-

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quency of the isolation system will change, and this will cause the change of isolation efficiency and thus affect the airframe vibration. On the other hand, the vibration environment on the top of rotor may have great influence on stability of the line-of-sight [5].

In this paper, the influence on dynamic behavior of FIS of Z-× helicopter equipped with MMS is investigated, which is the first time employed in China. The affection on airframe vibration of helicopter equipped with MMS will be discussed.

2 Dynamic Analysis of FIS with Dummy MMS

2.1 FIS of Z-× helicopter

The isolation system of Z-× helicopter is shown in Fig. 1. Four suspension bars, secured at one end to the main gearbox and at the other end to the fuselage, transmit the lift forces and moments generated by the rotor. An elastic suspension is mounted between main gearbox bottom and fuselage. Thus, the main gearbox can oscillate in longitudinal and lateral directions about the convergence point "O" of suspension bars. This is the so-called focal isolation system which enable the horizontal vibration caused by main rotor to be absorbed.

The mathematical model can be found in Ref [1], in which both the rotor and the fuselage are treated as rigid bodies. But the rigid body assumption is no longer suitable for rotor shaft when MMS has been put on the top of rotor. The elasticity of both the rotor shaft and the support part of MMS has to be taken into account.

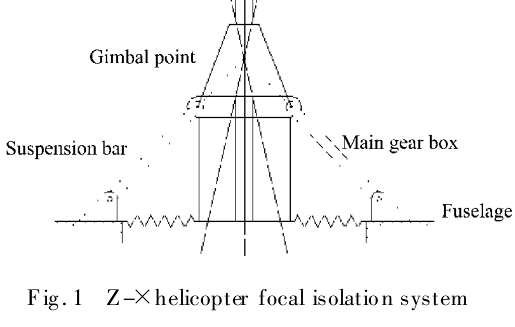

Fig. 1 Z-× helicopter focal isolation system

2.2 Formulation of analysis

A 5-DOF model has been proposed in this paper, as shown in Fig. 2, where m_1, I_1, m_2, I_2, m_3, I_3, m_4, I_4 are mass and rotational inertial of fuselage, main gearbox, rotor system and MMS, respectively.

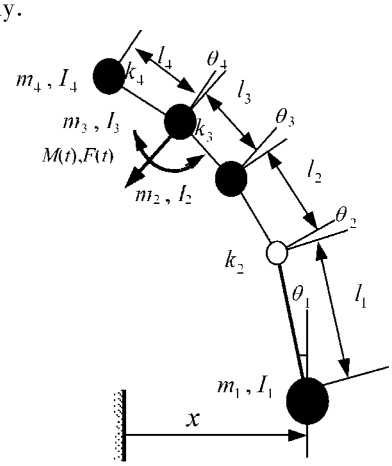

Fig. 2 Model of FIS/MMS/Fuselage couple system

The kinematic energy of the total system can be written as

$$\begin{aligned} T = {} & \frac{1}{2}I_1\dot{\theta}_1^2 + \frac{1}{2}I_2(\dot{\theta}_1 + \dot{\theta}_2)^2 + \\ & \frac{1}{2}I_3(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)^2 + \\ & \frac{1}{2}I_4(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \dot{\theta}_4)^2 + \\ & \frac{1}{2}m_1\dot{x}^2 + \frac{1}{2}m_2[\dot{x} + L_1\dot{\theta}_1 + l_2\dot{\theta}_2]^2 + \\ & \frac{1}{2}m_3[\dot{x} + L_2\dot{\theta}_1 + L_4\dot{\theta}_2 + l_3\dot{\theta}_3]^2 + \\ & \frac{1}{2}m_4[\dot{x} + L_3\dot{\theta}_1 + L_5\dot{\theta}_2 + L_6\dot{\theta}_3 + l_4\dot{\theta}_4]^2 \end{aligned} \quad (1)$$

the potential energy is

$$V = \frac{1}{2}k_2\theta_2^2 + \frac{1}{2}k_3\theta_3^2 + \frac{1}{2}k_4\theta_4^2 \quad (2)$$

and the work of external force is

$$\begin{aligned} W = {} & M(t)(\theta_1 + \theta_2 + \theta_3) + \\ & F(t)[x + L_2\theta_1 + L_4\theta_2 + l_3\theta_3] \end{aligned} \quad (3)$$

where

$$L_1 = l_1 + l_2,\ L_2 = l_1 + l_2 + l_3$$
$$L_3 = l_1 + l_2 + l_3 + l_4,\ L_4 = l_2 + l_3$$
$$L_5 = l_2 + l_3 + l_4,\ L_6 = l_3 + l_4$$

According to Lagrange equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \quad (4)$$

the equation of motion of the system is

$$\boldsymbol{M}\ddot{q} + \boldsymbol{K}q = \boldsymbol{Q} \quad (5)$$

where

$$\boldsymbol{q}^{\mathrm{T}} = \{x \quad \theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4\}$$

$$\boldsymbol{Q}^{\mathrm{T}} = \{F(t) \quad F(t)L_2 + M(t) \quad F(t)L_4 + M(t) \quad F(t)l_3 + M(t) \quad 0\}$$

Based on equation (5), the natural frequency of the system can be calculated while $\boldsymbol{Q}$ equal zero, and the transfer function $\boldsymbol{H}$ is

$$\boldsymbol{H}(\omega) = (\boldsymbol{K} - \omega^2 \boldsymbol{M})^{-1} \quad (6)$$

For shear excitation $F = F_0 \sin\omega t$ at the rotor hub, the response of fuselage is $\theta_1 = \theta_{10}\sin\omega t$, and

$$\frac{\theta_{10}}{F_0} = H_{21} + L_2 H_{22} + L_4 H_{23} + l_3 H_{24} \quad (7)$$

where H_{ij} is the element of matrix $\boldsymbol{H}$. In case of no isolation ($k_2 = \infty$),

$$\frac{\bar{\theta}_{10}}{F_0} = \bar{H}_{21} + L_2\bar{H}_{22} + L_4\bar{H}_{23} + l_3\bar{H}_{24} \quad (8)$$

In order to measure the effectiveness of an isolation system, the isolation efficiency is defined as the ratio of the given response to the response without isolation. Thus, the isolation efficiency for shear excitation $T_{\theta_1 F}$ is

$$T_{\theta_1 F} = \frac{\theta_{10}}{\bar{\theta}_{10}} = \frac{H_{21} + L_2 H_{22} + L_4 H_{23} + l_3 H_{24}}{\bar{H}_{21} + L_2\bar{H}_{22} + L_4\bar{H}_{23} + l_3\bar{H}_{24}} \quad (9)$$

On the other hand, the isolation efficiency can be defined as the ratio of the given response to the response of a prototype (without MMS), in order to measure the change of isolation efficiency after MMS equipped. Therefore

$$T'_{\theta_1 F} = \frac{\theta_{10}}{\theta'_{10}} = \frac{H_{21} + L_2 H_{22} + L_4 H_{23} + l_3 H_{24}}{H'_{21} + L_2 H'_{22} + L_4 H'_{23} + l_3 H'_{24}} \quad (10)$$

Where θ'_{10} is the fuselage response without MMS equipped.

By similar logic, the isolation efficiency $T_{\theta_1 M}$ and $T'_{\theta_1 M}$, with exciting moment applied at rotor hub, can be defined as

$$T_{\theta_1 M} = \frac{\theta_{10}}{\bar{\theta}_{10}} = \frac{H_{22} + H_{23} + H_{24}}{\bar{H}_{22} + \bar{H}_{23} + \bar{H}_{24}} \quad (11)$$

$$T'_{\theta_1 M} = \frac{\theta_{10}}{\theta'_{10}} = \frac{H_{22} + H_{23} + H_{24}}{H'_{22} + H'_{23} + H'_{24}} \quad (12)$$

3 Frequency Experiments of Z-× Helicopter with Dummy MMS

In order to make further research and to validate the analysis, frequency and transfer function tests on Z-× helicopter are carried out. A dummy MMS and its support structure are made, as shown in Fig. 3. The outer part of support structure rotates with the main rotor, the inner part is kept stationary by means of a stand pipe. The standpipe is installed in the main gearbox, from bottom to top, and fixed on the bottom. The rotor blades are substituted by dummy ones. The mass of the dummy MMS can be changed from 40kg to 80kg with every 20kg. According to analysis, the mounted height of MMS is 930mm. Table 1 shows the details of the concerned parameters both in longitudinal and in lateral directions.

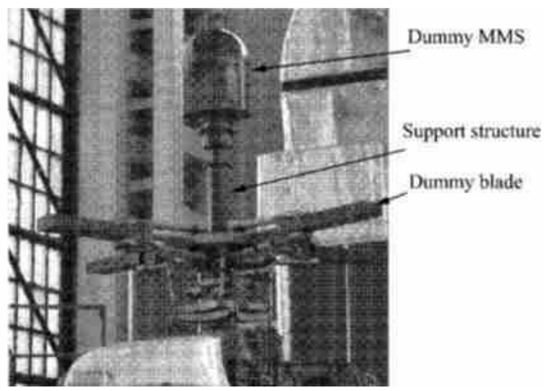

Fig. 3 MMS installation during experiment

Table 1 Details of concerned parameters

	Longitudinal	Lateral
M_1/ kg	3300	3300
I_1/ (kg·m^2)	12489	3129
M_2/ kg	230	230
I_2/ (kg·m^2)	25	20
M_3/ kg	333	333
I_3/ (kg·m^2)	15	15
M_4/ kg	40, 60, 80	40, 60, 80
I_4/ (kg·m^2)	2	2
l_1/ m	1.637	1.467
l_2/ m	−0.58	−0.38
l_3/ m	0.939	0.939
l_4/ m	0.93	0.93
K_2/ (N·m·rad^{-1})	1008250	359307
K_3/ (N·m·rad^{-1})	7487076	7487076
K_4/ (N·m·rad^{-1})	793973	793973

The helicopter is steady on the ground, while exciter is hanged by an elastic rope, and excites on the dummy blade. During the frequency test, the sensors are set not only on MMS, support structure and main gearbox, but also on airframe to identify the frequency mode. Transfer functions from the center of rotor to pilot seat and MMS, are tested, with shear force loaded only.

4 Results and Discussion

Fig. 4 shows the first and second longitudinal frequencies, when the mass of MMS varies from 40kg to 80kg with the mounted position kept constant (l_4 = 930mm). The variation tendencies of experiment results and analysis results are same for the first order frequency, in which the analysis results are much higher with an error from 2.95% to 5.57%, and the error increases with the mass of MMS increased. The 1st order frequency decrease 39% when the weight of MMS is 80kg, which is only 12% of the mass to be isolated, as compared to prototype. For the second order frequency, the error varies from 4.43% to −4.58%.

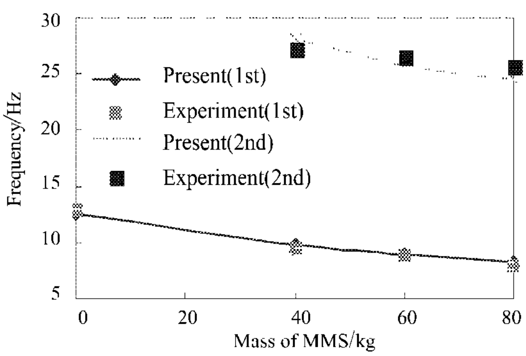

Fig.4 Comparison of longitudinal frequencies of experiment and analysis results

The correlation of lateral frequency is shown in Fig.5. For the first order frequency, there is an error from 1.78% to −2.63% between test and calculation. For the second order frequency, the error is from 4.12% to −0.54%.

Fig.6 shows the frequency variation when the mounted height (l_4) varies from 700mm to 1100mm with a MMS of 60kg. The second order frequency decrease more rapidly than that of first

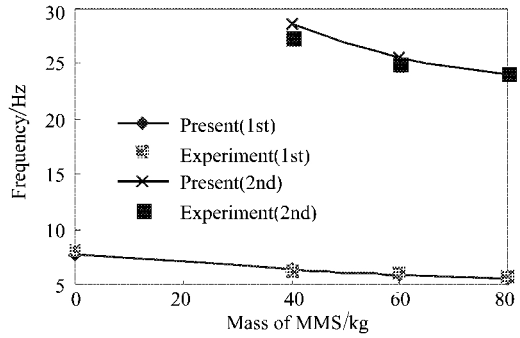

Fig.5 Comparison of lateral frequencies of experiment and analysis results

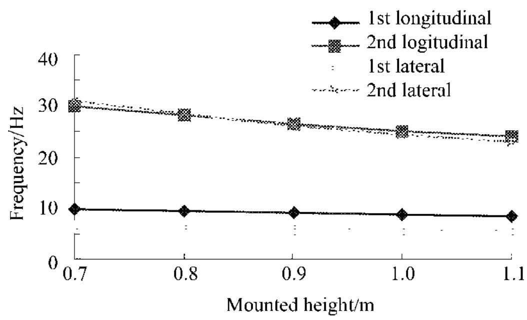

Fig.6 Frequency of isolation system corresponding to mounted height

order frequency when the mounted height increases.

Table 2 compares the calculated isolation efficiencies in longitudinal direction, in which the excitation frequency is 24Hz, with the results of rigid body model in Ref[6], by making the K_3 and K_4 1000 times increasing of present model, and good correlation are obtained.

Table 2 Comparison of the calculated isolation efficiencies with results in Ref[6]

MMS Mass /kg	$T_{\theta_1,F}$ Present	$T_{\theta_1,F}$ Ref[6]	$T_{\theta_1,M}$ Present	$T_{\theta_1,M}$ Ref[6]
0	0.7753	0.7732	−0.132	−0.1402
40	0.713	0.7115	−0.546	−0.553
60	0.706	0.7047	−0.638	−0.6437
80	0.7038	0.7026	−0.707	−0.7127

Fig.7 shows the variation of isolation efficiencies of the prototype while the stiffness of rotor shaft (K_3) varies from K_3 to $24\times K_3$, where subscribe x and y indicate longitudinal and lateral directions, respectively. The isolation efficiencies increase rapidly while the stiffness of rotor shaft increases, and converges gradually to the results calculated with the model in Ref[6], $T_{\theta_1 M_x}$ varies from − 0.2206 to − 0.89 with 403% increased, when the ratio of stiffness (K/K_3) varies from 1 to 24, while in the other three have increases 208%, 232% and 322%, respectively, which indicates the elasticity of rotor shaft should be taken into account even for the prototype.

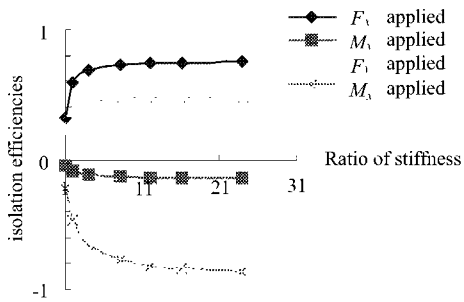

Fig.7 Isolation efficiencies of prototype corresponding to ratio of stiffness K_3

Fig. 8 shows the variation of the isolation efficiencies $T'_{\theta_1 F}$ in longitudinal direction. Both the calculated present results and the experimental results indicate that fuselage the response with 40kg or 60kg MMS is lower than that of the prototype, and the response is much higher when 80kg MMS is equipped, which shows that the mass of MMS has great influence on isolation efficiency of FIS of Z-× helicopter, while the response calculated with the model in Ref[6], decreases slightly when the mass of MMS increases. There is some difference in value between the calculated results and the experiment results when the mass of MMS is 40kg and 60kg, and the possible reason is that the fuselage is assumed as rigid body in present model while the real fuselage is elastic one, especially in the longitudinal direction. The calculated results approach the experiment results when MMS is 80kg, because of the elastic effect decrease as the excitation frequency is close to the second order natural frequency of MMS.

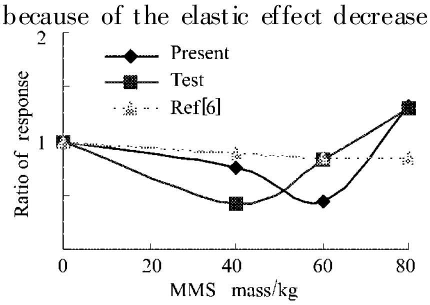

Fig. 8 Comparison of $T'_{\theta_1 F}$ in longitudinal between analysis and experiment

Fig. 9 shows the variation of the isolation efficiencies $T'_{\theta_1 F}$ in lateral direction. Good correlation between the calculated results and the experimental results is achieved, which shows that the rigid body assumption of fuselage in lateral direction is reasonable. With 40kg or 60kg MMS equipped, the response of fuselage is nearly the same with the prototype, while the response is higher than that of prototype when MMS is 80kg.

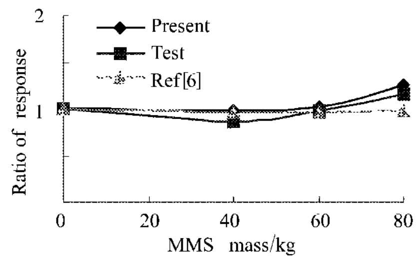

Fig. 9 Comparison of $T'_{\theta_1 F}$ in lateral between analysis and experiment

5 Conclusions

A dummy MMS and its support structure are manufactured to investigate the influence of MMS on focal isolation system's dynamical behavior. Good correlation between analysis and experiment is achieved. Based on this study, the following conclusions are made.

(1) MMS has great influence on the frequency and isolation efficiency of focal isolation system.

(2) The elasticity of rotor shaft and MMS structure has great influence on the normalized response of fuselage, even for the prototype.

(3) In order to avoid coalescence with the forcing frequency of rotor, the second order frequency of the isolation system must be taken into account when MMS is employed, which means that the mounted height and the stiffness of support structure must be carefully designed.

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